Quarkonium and B_c meson production in heavy-ion collisions

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Quarkonium in heavy ion collisions: theory meets experiment

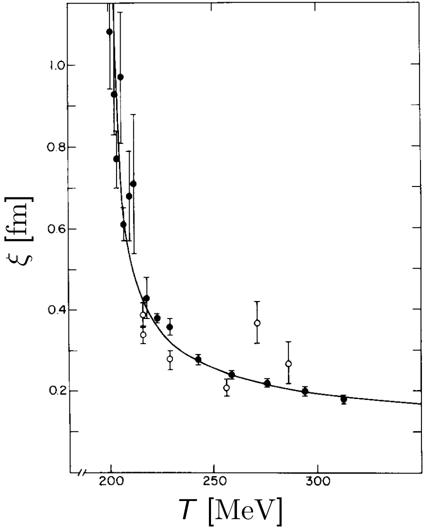
Dynamics of heavy quarks and quarkonium

Monte Carlo for heavy quarks and quarkonium

Another particle: B_c mesons

J/ψ suppression

At high temperatures, electric fields are screened, changing the quarkonium spectrum.



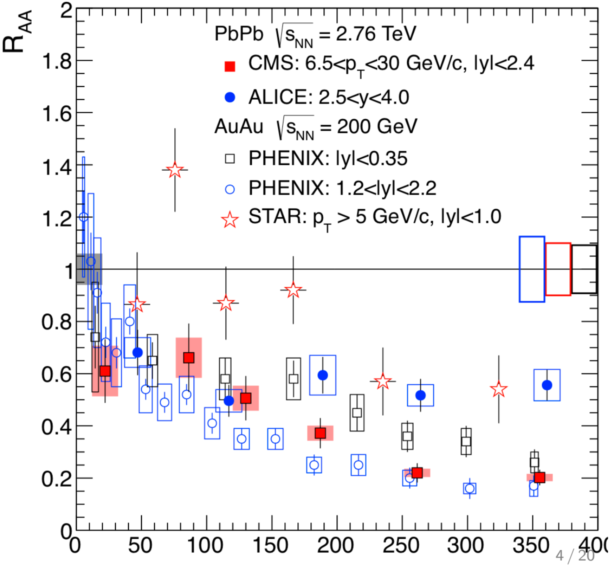
Matsui and Satz: Correlator of a color singlet system $\Gamma \sim \exp(-r/\xi(T))$. $\xi(T)$ steadily drops with T, at some point going below r_{Bohr} for the J/ψ. At this temperature, the J/ψ is *suppressed*.

This suggests J/ψ particles do not exist in much of the heavy-ion collision; they are strongly suppressed.

J/ψ suppression: the reality

Complicated suppression pattern: the "minimum" of R_{AA} apparently reached at RHIC. ALICE finds R_{AA} *flat* in N_{part}.

R_{AA} exhibits an extremely complex set of dependencies on T, $\sqrt{s}$, and p, unexplained by Matsui and Satz.



Revisiting quarkonium at finite T

Possibly important missing pieces:

- The quarkonium spectrum examined directly in lattice QCD: $\int d^3x \, \langle J_\mu(\mathbf{x},\tau) J^\mu(\mathbf{0},0)\rangle$, $\rho(\omega)$ extracted (Datta et al.).
- Examining which potential (U, F,...) best describes the quarkonium spectrum at $T \sim T_c$ (Mocsy and Petreczky, Shuryak and Zahed).
- J/ψ forms early and evolves *dynamically* (Rapp and Zhao, CY and Shuryak).
- Recombinant production enhances production at large $\sqrt{s}$.

Revisiting quarkonium at finite T

However:

Greatly differing models of quarkonium production *still exist* (statistical hadronization without dynamics, Matsui-Satz models with sequential suppression).

The physics of these models are radically different!

Cold nuclear matter effects, experimental cuts, and the opposite signs of recombinant production and suppression make charmonium very difficult to use as a decider for the validity of theoretical models; however, charmonium with bottomonium provide some hints.

A state produced only recombinantly would be extremely useful (more on that later).

A single heavy quark above deconfinement

When $M \gg T, p$, the dynamics described by $3\kappa = \int d^3q |\mathbf{q}|^2 \frac{d\Gamma}{dq^3}$.

How to determine?

- HTL effective theory (poor convergence from LO to NLO for realistic α_s) (Moore and Teaney, Caron-Huot and Moore).
- Lattice QCD (analytic continuation of Euclidean correlators difficult).
- AdS/CFT for strongly-coupled gauge theories (not QCD) (Gubser, Casalderrey-Solana and Teaney).

Current phenomenology of heavy quark elliptic flow gives $3\kappa \approx 4T^3$, larger than LO HTL estimates but smaller than in strongly-coupled $\mathcal{N} = 4$ SYM theory.

A single heavy quark above deconfinement

When $M \gg T$ and $\gamma v \lesssim 1$, dynamics described by the relativistic Langevin equation:

$$\frac{dp^i}{dt} = -\eta p^i + \xi^i(t), \quad \left\langle \xi^i(t)\xi^j(t') \right\rangle = \kappa \delta^{ij} \delta(t - t').$$

Requiring $\langle p^2(t) \rangle$ to approach the thermal value gives the Einstein relation:

$$\eta = \kappa / 2MT$$

Modelling *quarkonium* with Langevin dynamics

Loosely bound quarkonium can also be described with a relativistic Langevin equation. For each quark J in a pair forming quarkonium,

$$\frac{dp^i_J}{dt} = -\eta p^i_J + \xi^i_J(t) - \frac{\partial V(\mathbf{x}_K)}{\partial x^i_J},$$

$$\left\langle \xi^i_J(t)\xi^j_K(t') \right\rangle = \kappa\delta^{ij}\delta^{JK}\delta(t-t').$$

Disassociation of J/ψ now dynamical, includes the physics of potentials with both real and imaginary parts. A satisfactory description at strong coupling.

Heavy quark hadronization at freeze-out

In elementary collisions, *color evaporation model*: if $M < 2M_D$, where $M = \sqrt{(p_1 + p_2)^2}$, the heavy quarks form a quarkonium state. Simple, successful across experiments (color singlet model underpredicts, color octet (NRQCD) model has many parameters).

However, in AA collisions, how to take into account non-trivial evolution in momentum *and position*?

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Modified color evaporation model: $M = \sqrt{(p_1 + p_2)^2} + V_{\mathrm{Cornell}}(r_{\mathrm{CM}})$.

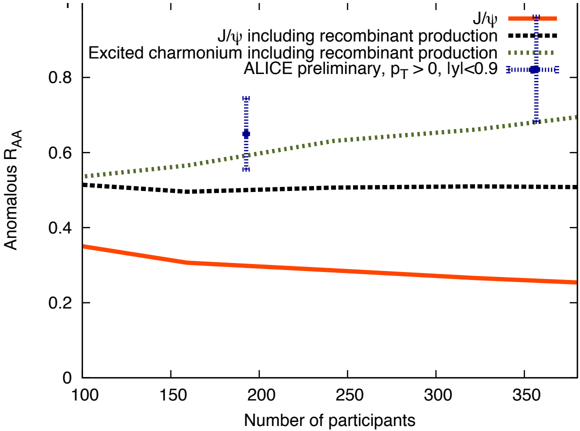
Useful for calculating recombinant production (Q and $\bar{Q}$ from separate perturbative processes) and B_c yields.

MARTINI for heavy quarks

Monte Carlo a necessity for any comparison of theory with RHIC or LHC results. MARTINI (Schenke, Gale, Jeon, CY) follows the following steps:

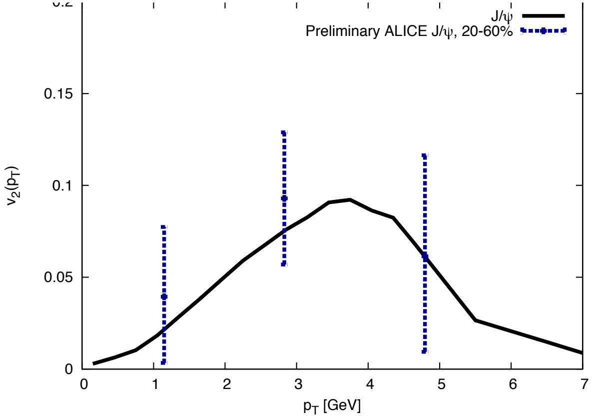
- Shadowing and anti-shadowing of pdf's, averaging over isospin
- PYTHIA8 for multiple final states via parton showering
- Solving of the relativistic Langevin equations numerically, for an ensemble of heavy quark pairs, informed by the 3+1-dimensional hydrodynamical evolution calculated by MUSIC (Schenke et al. 2009)
- Hadronization using the modified color evaporation model

R_{AA} for J/ψ and MARTINI



The surviving component of the J/ψ yield not enough to explain the total yield. Including recombinant production is needed.

D and J/ψ $v_2(p_T)$ with MARTINI

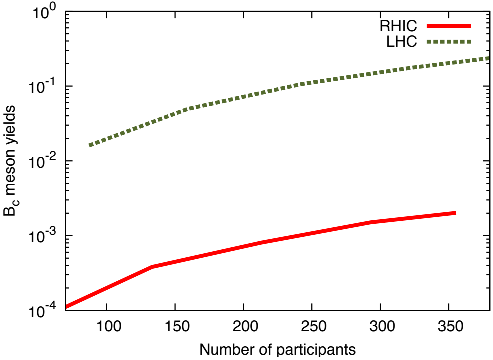


Flow of J/ψ and D mesons explained with different kinetic freeze-out temperatures for the different mesons (sequential freeze-out).
$T_{\rm kin} = 190\ \mathrm{MeV}$ consistent with Euclidean quarkonium correlators.

B_c meson production

B_c mesons are predicted for heavy ion collisions (Schroedter et al. 2000); the yields for these states in elementary collisions are small.

- Mostly produced recombinantly, testing models for in-medium hadronization.
- Sensitive to heavy quark densities at hadronization; an indirect probe of T_{ch} for quarkonia.
- Measurements at RHIC and the LHC *complementary*.



My question for this audience:

$B_c \to J/\psi + \mu^+ + \bar{\nu}_\mu \to \mu^+ + \mu^- + ...$:

VTX is expected to determine the contribution of B mesons to J/ψ yields.

B_c mesons are distinguished from other B mesons by its large invariant mass $\to$ analysis of B_c meson yields would use $\sqrt{p_{J/\psi}^2 + p_\mu^2}$.

Can PHENIX and STAR devote resources to analysis of B_c yields?

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